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EVALUATION OF COMMUNICATION DURING ACTIVE SONAR TRANSMISSIONS WITH A SPEECH-RECOGNITION MODEL

Lynne Marshall
Thomas E. Hanna
and
Chaslav V. Pavlovic

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P. K. Weathersby, CAPT, MSC, USN
Commanding Officer
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Lynne Marshall, Ph.D. and Thomas E. Hanna, Ph.D.
Naval Submarine Medical Research Laboratory

Chaslav V. Pavlovic, Ph.D.
University of Iowa

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SUMMARY PAGE

PROBLEM

To determine whether intense tones in the frequency region around 1000 Hz might affect speech recognition in background noises similar to those found on ships.

METHOD

The Speech Intellibibility Index (SII) was used to quantify the expected acoustic interference of tones around 1000 Hz and pink noise. The tones simulate an active-sonar system that would radiate back through the ship's compartments. The pink noise simulates shipboard background noise.

FINDINGS

A speech-recognition model predicted that speech-recognition could remain high in the presence of the intense tonal maskers, but that speakers would have to raise their voices, often to a shout, in order to maintain intelligibility. Results with actual speakers and listeners verified this prediction.

APPLICATION

Intermittent, intense tones should not create undue problems for speech communication. The tones in this study had a 6-sec duration with a 24-sec rest between tones, as might be used for an active-duty cycle. If the tones were on for longer durations, however, listeners might have difficulty maintaining the high voice levels required for communication. In addition, if listeners are working on complex tasks or under stress, their speech understanding might decrease markedly. Other factors that could markedly decrease speech understanding, especially in combination with high levels of background noise and high levels of task complexity, include a listener with a hearing loss, a speaker with unclear speech, or a poor transmission system distorting the speech signal.

ADMINISTRATIVE INFORMATION

This research was carried out under a task plan entitled, "Development of acoustic habitability standards for ships' spaces subjected to intense tones" and was funded by Program Executive Office Surface Ship ASW Systems Task No. SSAS-91-77A01R2 dated 14 December 1990 "AN/SYQ-1 Frequency Array testing", Naval Sea Systems Command PMO 424. The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. This report was approved for publication on 30 July 1993, and designated as NSMRL Report 1188.

ABSTRACT

Predictions using the Speech Intelligibility Index (SII) are reported for speech recognition in tonal and broadband noise. Three levels of background pink noise (60, 65, and 70 dBA) were used for the SII. Tones in the frequency range around 1000 Hz at 77, 83, and 89 dB SPL were added to the background pink noise. The speech spectra were for four different vocal efforts (normal, raised, loud, and shouted). The simulated listeners for most of the predictions were assumed to have normal hearing. A hearing loss was also included for a subset of predictions. If "barely adequate" speech recognition is used as a criterion, the effects of the background noise can be overcome by increasing the vocal effort of the speaker, often to a shout.

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EVALUATION OF COMMUNICATION DURING ACTIVE SONAR TRANSMISSIONS WITH A SPEECH-RECOGNITION MODEL

The purpose of the present investigation was to estimate the extent to which active sonar sounds from a new sonar system would interfere with speech recognition on ships. Speech-recognition performance was modeled using the Speech Intelligibility Index (ANSI, 1992). The Speech Intelligibility Index (SII, which was formerly known as Articulation Index, or AI) is the proportion of the total speech information reaching the ear of the listener, with each frequency band weighted by its relative importance. The maximal value of the SII (1.0) means that all acoustic information is present; the minimal value (0.0) means that no acoustic information is present. Similarly, a value of 0.5 means that half of the information is present. As a general guideline, "excellent" speech understanding occurs for SIIs above 0.75, "good" is between 0.6 and 0.75, "fair" is between 0.46 and 0.6, "poor" is between 0.3 and 0.45, and below 0.3 is "bad" (IEC, 1988).

In a noise background, the proportion of the speech that is above the noise determines the SII and, thus, speech understanding. A fundamental effect of noise on speech production is that vocal effort increases with increasing background noise levels. As vocal effort increases, there are two changes in the speech spectra. The first is that the overall level increases. The second is that the spectral shape changes; there is more high-frequency emphasis with increased vocal effort. Thus, it is important to include the effect of vocal effort in estimating speech understanding in background noise.

Pearsons (personal communication, 1988) suggested (based on work under contract to the Environmental Protection Agency) that people raise their voice to maintain 95% correct sentence recognition, which is equivalent to an SII of approximately 0.45. In general, the lower cut-off for barely adequate communication is considered to be 0.45 or 0.46. At this SII, scores for single one-syllable words out of context are considerably lower (around 70% correct) than for sentences. Thus, communication situations that depend on single words out of context require higher SIIs.

In the present paper, we provide SIIs at three background levels of a tonal complex used to simulate the active sonar of interest. Four vocal efforts are presented ranging from normal to shouted speech. The effects of hearing loss also are briefly discussed.

Method

The modeled speech signal was the average speech spectrum of male and female speech as measured in free field, one meter from the talkers' lips for four vocal efforts -- normal, raised, loud, and shout (Pavlovic, Rossi, and Espesser, 1990). For normal, raised, loud, and shouted vocal efforts, the overall levels of speech are 62.4 dB SPL, 68.3 dB SPL, 74.8 dB SPL, and 82.3 dB SPL respectively.

The speech spectrum undergoes two additional changes in the hearing process. The first is that the head and external ear (pinna and ear canal) alter the spectrum via their resonance characteristics (i.e., transfer function). The second is that, in the inner ear, energy from some frequency bands may spread to others, especially at higher intensity levels (i.e., masking). The same factors affect the noise spectrum. The present model uses a free-field-to-eardrum transfer function (Bentler and Pavlovic, 1989), and the spread of masking across bands was calculated according to Ludvigsen (1985).

At higher levels of speech input, increases in the speech level do not increase the speech recognition at the same rate as at lower levels. In the current model, a decreasing proportion of the speech energy contributed to the SII at higher levels (above approximately 72 dB SPL).

The speech and noise spectra were divided into 18 1/3-octave bands (with center frequencies from 160 to 8000 Hz) for this analysis. The weighting for the relative importance of each frequency band in the speech signal is dependent on the speech materials used.[1] The importance function for this analysis was the frequency-band weightings averaged across several types of speech materials (e.g., nonsense syllables, monosyllabic meaningful words, easy running speech) (Pavlovic, 1987).

The background noise used in our SII calculations had two components. The first was pink noise,[2] which approximates the measured backgrounds in many compartments of surface ships. Three levels of pink noise, 60, 65, and 70 dBA were used. The levels 60 dBA and 65 dBA are maximum permissible levels of continuous broadband noise on Naval vessels for category A-12 (talker-listener distance 6 feet or greater) and C (quiet essential; e.g., sonar and medical) spaces, respectively (CNO, OPNAVINST 9640.1, 1979). The 70 dBA level is specified both for A-3 spaces, where talker-listener distances are less than three feet (e.g., small offices), and for areas where the primary consideration is comfort (e.g., berthing areas and wardrooms). The second background noise component was pure tones at the frequencies of 720, 800, 880, 960, 1040, and 1120 Hz, which simulated active sonar pings. The model assumed that one of these tones was always present, with each being equally represented.

1 Speech understanding is influenced by the redundancy of the speech; the greater the speech redundancy, the easier it is to understand and the less it will be degraded in difficult listening situations. The frequency distribution of the usable informational content of the signal also is affected by the speech redundancy. For example, the frequency band with the highest weight in the importance function for a typical set of nonsense syllables is 2500 Hz while for a typical sample of running speech is 450 Hz. See Pavlovic (1987) for more details.

2 Pink noise has a continuous frequency spectrum with spectrum level decreasing at 3 dB/octave, which has the result of having equal energy within a bandwidth proportional to the center frequency of the band.

The hypothetical listeners for our calculations had normal hearing (0 dB HL thresholds at all frequencies) and were listening binaurally.

Speech-recognition data also were collected on Navy enlisted personnel who were in the laboratory as subjects for habitability studies on the effects of the active-sonar pings. All had normal hearing thresholds (less than or equal to 15 dB HL from 125 through 8,000 Hz). Five or six subjects lived in the laboratory at the same time. For the speech tests, each subject was the speaker for one 50-word list of the Modified Rhyme Test (Kreul et al., 1968). The monosyllabic words take the form of consonant-vowel-consonant (e.g., "bad"). The test has a six-alternative, closed-set test format in which, for each test item, the listener has six words to choose from (the test word and five foils, which differ from the test word by either the initial or final consonant).

Each subject practiced the assigned list by reading it aloud to the experimenter. Any mispronunciations were corrected during the practice time. During the test, the talker used the phrase, "Mark ___, ___, and ___ please," using connected speech with three words from the list to approximate normal speaking conditions. For each list, one subject was the talker, and the other subjects were the listeners. The talkers were given no specific instructions about vocal effort, but rather were asked to speak normally. Most, however, tended to speak more slowly and loudly with more precise pronunciation when reading the word lists to the group in the test situation than they did in informal conversations.

Details of the physical and acoustical characteristics of the test room are given in Sylvester (1993). Both talkers and listeners were seated on their beds during the testing. The subjects were given no instructions about whether to watch the speaker. Although watching the speaker would have been a good strategy because visual cues aid speech understanding, the subjects looked at the answer sheet instead of the talker.

Testing occurred over three sequential days. On each of the three days, the subject read the same list, but the word order was varied on each day. On the first day, the test was administered in the room with no additional noise added (roughly in the 46-51 dBA average range). On the second day, 60 dBA pink noise was added to the room. On the third day, both the 60 dBA pink noise and the active-sonar pings at the particular level assigned to that subject group were present. For two groups, two additional days of testing took place to assess learning effects. Day 4 was the pink-noise condition (like Day 2), and Day 5 was a repeat of Day 1, with no additional noise added to the room.

Results

A. SII and pings.

SIIs, assuming normal-hearing listeners, for 60 dbA background noise are shown in Figure 1 (left panel) (the right panel shows a simulated hearing loss, which will be discussed in the next section). SIIs for 65 and 70 dBA background noise are shown in Figure 2. (All SII values also are included in tabular form in the Appendix). Each panel of the figures shows SIIs for the pink noise alone and with three levels of tones -- 77 dB SPL, 83 dB SPL, and 89 dB SPL. The speech spectra are for normal, raised, loud, and shouted speech.

In order to maintain barely adequate speech communication (i.e., SII= 0.46 or greater) in a 60 dBA noise background (Figure 1, left panel), speakers must use a raised voice. With 77, 83, or 89 dBA tones added to the

background noise, they must speak loudly. The speech levels predicted from the SII model are consistent with observed speech levels of talkers during a speech communication task.

In order to maintain barely adequate speech communication in the 65 dBA broadband noise background (Figure 2, left panel), the speaker must use a raised voice, and, when the tones are added at 77 and 83 dB SPL, must speak loudly. With the addition of an 89 dB SPL tone, the speaker must shout. In 70 dBA background noise, the speaker must speak loudly, and, the addition of the tone (at all three levels) requires the speaker to shout.

B. Effect of hearing loss on SII

The effects of a hearing loss also were modeled. Thresholds of 20, 30, 35, 40, 55, 90, and 90 dB HL at 0.5, 1, 2, 3, 4, 6, and 8 kHz, respectively, were modeled as a simple attenuation (change in threshold levels), as per the draft ANSI standard (ANSI, 1992).

We know of no recently published studies of the hearing levels of officers, but high-frequency hearing-threshold elevations of this magnitude are found among the enlisted active-duty population (NEHC, 1990).

Figure 1 (right panel) shows the effect of the simulated hearing loss. As expected, the SIIs are lower for the listener with hearing loss. Also, there is less improvement with increased vocal effort if the listener has a hearing loss. The high-frequency acoustic information that is available to the normal-hearing listener at increased vocal efforts is not available to a listener with a high-frequency hearing loss. For our simulated listener with hearing loss, the loss at 4000-5000 Hz was the predominant cause of the decreased SIIs. (Band-by-band speech-to-noise ratios illustrating this effect are given in the Appendix in Table AP-V.) Noise-induced hearing loss, which is the most frequent cause of hearing impairment in the Navy, typically is maximal at 4000 Hz. As can be seen in Figure

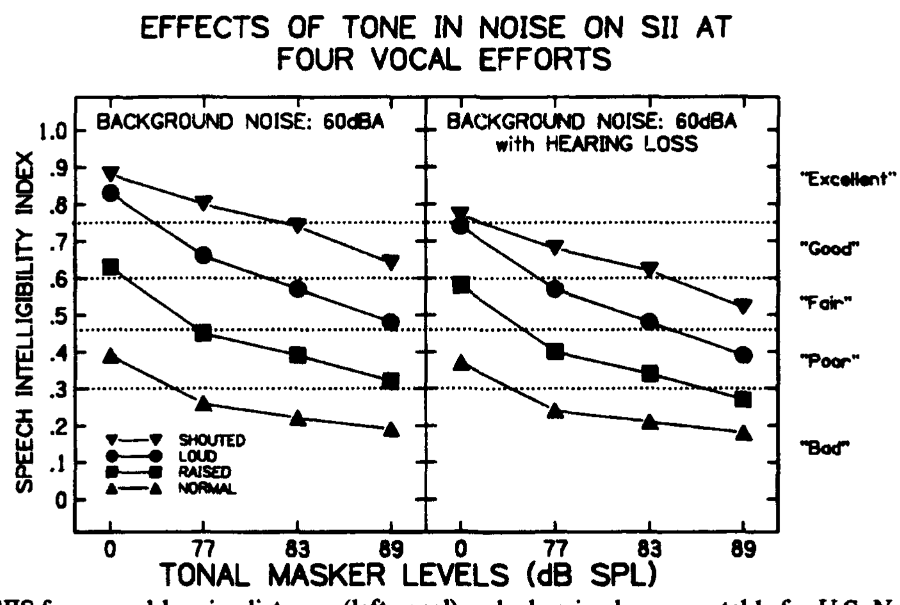

Figure 1. SIIS for normal-hearing listeners (left panel) and a hearing loss acceptable for U.S. Naval officers (right panel). The background noise in both cases is 60 dBA pink noise with a tonal masker (1000-Hz region) added at 77, 83, and 89 dB SPL. An SII of 0.46 is considered barely adequate communication.

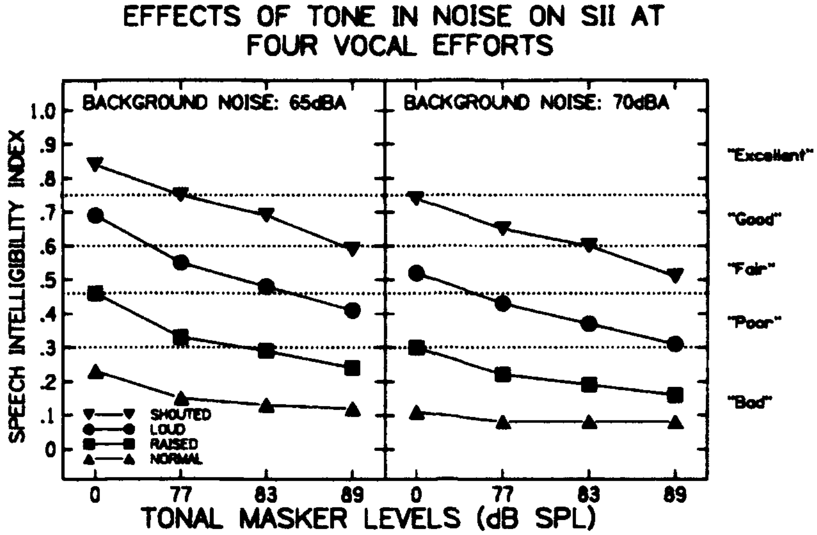

Figure 2. SIIs for normal-hearing listeners in 65 (left panel) and 70 (right panel) dBA pink noise. As in Figure 1, a tonal masker (1000-Hz region) is added at 77, 83, and 89 dB SPL.

1, this hearing-impaired listener requires greater vocal effort from the speaker to achieve an SII comparable to a normal-hearing listener. Note that in the 60 dBA background noise used in our simulations, a normal-hearing listener needs a raised voice level, but the hearing-impaired listener needs a loud voice level for barely adequate communication.

We did not incorporate the increase in upward spread of masking that accompanies increasing hearing loss (as modeled by Ludvigsen, 1985, and Humes, Espinoza-Varas, and Watson, 1988) because there is much individual variability in the size of this effect, and there is no consensus on appropriate modeling of hearing loss. Therefore, our calculations are an upper limit on the SII, and the performance of groups of hearing-impaired listeners actually would be expected to be somewhat poorer than we have shown. In addition, there is variability among the individual listeners' performance, especially for hearing-impaired listeners. That is, it is well known that some hearing-impaired individuals have much poorer speech recognition than others with simliar amounts of hearing loss.[3] These individual differences may well be accounted for by differences in spread of masking. For example, Dubno, He, Schaefer, and Ahlstrom (1992) found that taking into account individual amounts of spread of masking for SII calculations greatly improved the ability to accurately predict the relationship between SII values and speech-recognition scores. Accurately predicting both mean data and the range of performance for hearing-impaired listeners remains to be done.

3 The audiogram describes only one component of a hearing loss. It is not surprising that individuals with similar audiograms differ in other aspects of hearing such as frequency discrimination and uncomfortable loudness levels.

Table 1
Word-recognition scores for seventeed subjects in three background noises. The numbers in parentheses below the scores are standard errors of the mean.

Ambient room noise	Pink noise (60 dBA)	Pink noise (60 dBA) + 89 dB pings
90.1% (1.0)	82.7% (1.1)	78.6% (1.7)

C. Actual speech-recognition scores with 89 dB pings

Word-recognition scores are given in Table 1 for the seventeen subjects who listened in the presence of 89 dB pings. Individual scores were computed for each list, and all the scores from each individual for one day (one condition) were averaged. Then the scores for all the subjects on each day were averaged. Because these were essentially unpracticed talkers/listeners, practice effects were seen as determined by comparisons of the scores on Days 2 and 4 (pink noise) and Days 1 and 5 ("quiet;" i.e., ambient room noise) for the two groups in which scores were measured for five, rather than just three, days. The use of a closed-set test eliminated the listener effects due to learning the speech materials. Another factor that affects listeners, however, is learning to listen in particular acoustic conditions or becoming accustomed to a talker's speech pattern. Many of the talkers spoke more clearly and at higher levels as they became more practiced. In order to correct for learning effects, we decided to reference the scores to the third day (ping day). A correction factor for learning was determined by averaging the scores for the two days that had the same condition (Days 2 and 4, and Days 1 and 5), using the data for the two groups (twelve subjects) that were tested across five days, and then subtracting the difference between the initial test for a particular condition (Day 1 for "quiet" and Day 2 for "pink noise") from the average. This correction factor was added to the average score for the seventeen subjects. The correction factor was 2% for ambient noise only (Day 1) and 1.8% for the pink noise (Day 2).

As the signal-to-noise ratio decreased, the word-recognition scores decreased, as expected. They would have decreased more except that the speakers increased their vocal effort as the background noise increased. In no condition were the word-recognition scores even close to perfect. The primary reason probably is that the listeners were always listening in a noise background at levels sufficient to mask portions of the speech.

Our impression is that factors such as regional accents and inattention influenced few individual scores and thus had a minimal effect on the mean scores.

The relative decrements across conditions is consistent with the trend predicted by the SII analysis. The exact decrement in percent correct cannot be predicted from the SII values because the transfer function between SII and percent correct for our particular set of speakers and speech materials is unknown.

Conclusions

Our conclusion is that, given the low duty cycle (20%) of the active sonar, (i.e., on for 6 seconds, off for 24 seconds), speakers probably can compensate for the interference of the tones, even at 89 dB, by increasing the vocal effort, often to a shout, while the active sonar is activated. If the sonar had a higher duty cycle, our conclusion would become more conservative because people would be required to maintain greater vocal effort for longer periods of time. Not only might they be unwilling to maintain a high level of vocal effort over long periods of time, but they also would become hoarse, with a resultant inability to maintain the required vocal intensity.

For particular applications, there are other factors that need to be considered. All of these would result in a more conservative conclusion.

(1) We have assumed that the talkers speak clearly and distinctly. Presumably, even if a speaker's actual speaking style is less clear, training can improve speech clarity in noisy backgrounds.

(2) Our recommendations assume that all listeners have normal hearing. However, hearing losses that are acceptable according to Navy standards will lower the SIIs if the hearing loss is sufficient to filter out speech acoustical information. In addition, many listeners with hearing losses also have more upward spread of masking than predicted by this SII model. The effective result is greater perceived noise for the hearing-impaired listeners and thus lower SIIs. The actual hearing levels of personnel using particular spaces should be taken into account in determining whether communication in a particular space will be adequate.

(3) Speech transmitted through communication systems (which often are band-limited and distorted) often results in lower speech recognition. If speech understanding in an area is already only "barely adequate" due to background noise levels, distortions in the speech signal over communication systems can easily decrease speech understanding to unacceptable levels. In addition, the talker may be communicating from a relatively quiet environment to the listener's noisy environment and may not adequately compensate for the low signal-to-noise ratio in the listener's space.

(4) These SIIs assume that the listener is able to give full attention, both mentally and visually, to the talker. If performing a complex task or several tasks simultaneously (i.e., high cognitive load or divided attention tasks), or if performing under stress, speech understanding could be lowered. Also, in stressful situations, the talkers' speech may deteriorate; they may speak more rapidly and less clearly. If these conditions are likely to occur in particular environments, a higher SII may be required for reasonably good communication.

(5) For these reasons, a more stingent requirement for speech should be considered if understanding must be quick and accurate during the six-second active-sonar interval. The importance of good speech recognition has been recognized by the Chief of Naval Operations, who specified that "direct speech communication must be understood with minimal error and without need for repetition" in Category A spaces (OPNAVINST 9640.1, 1979). Unfortunately, this description is incongruent with the permissible back-

ground noise levels in this same document. The noise levels are too high to permit such good speech recognition.

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APPENDIX

Note: Tables A-1 through A-4 are SIIs at several background noise levels. These SIIs are plotted in the text as Figures 1 and 2.

Table A-1
SIIs for four speech levels (from normal to shout) with a pink-noise background of 60 dBA and tones (sequentially presented tones in random order at 720, 800, 880, 960, 1040, and 1120 Mz) at 77, 83, and 89 dB SPL. The listener has normal hearing.

	MASKER			
SPEECH LEVEL	PINK 60	PINK 60+ TONE 77	PINK 60+ TONE 83	PINK 60+ TONE 89
NORMAL	0.387	0.255	0.222	0.189
RAISED	0.630	0.450	0.393	0.324
LOUD	0.829	0.657	0.573	0.479
SHOUT	0.883	0.802	0.740	0.637

Table A-2
SIIs as in Table I except with a pink-noise background of 65 dBA.

	MASKER			
SPEECH LEVEL	PINK 65	PINK 65+ TONE 77	PINK 65+ TONE 83	PINK 65+ TONE 89
NORMAL	0.291	0.188	0.170	0.156
RAISED	0.485	0.379	0.356	0.321
LOUD	0.735	0.632	0.584	0.527
SHOUT	0.922	0.860	0.817	0.754

Table A-3
SIIs as in Table I except with a pink-noise background of 70 dBA.

	MASKER			
SPEECH LEVEL	PINK 65	PINK 65+ TONE 77	PINK 65+ TONE 83	PINK 65+ TONE 89
NORMAL	0.114	0.081	0.080	0.080
RAISED	0.305	0.217	0.189	0.157
LOUD	0.524	0.429	0.373	0.314
SHOUT	0.740	0.652	0.596	0.514

Table A-4
SIIs as in Table I except with a hearing loss allowable for an officer in the U.S. Navy.

	MASKER			
SPEECH LEVEL	PINK 60	PINK 60+ TONE 77	PINK 60+ TONE 83	PINK 60+ TONE 89
NORMAL	0.371	0.239	0.206	0.176
RAISED	0.576	0.396	0.338	0.272
LOUD	0.739	0.567	0.483	0.392
SHOUT	0.767	0.685	0.624	0.524

Table A-5
Speech-to-noise ratios (SNRs) modeled (SII) with a normal vocal effort, pink noise at 60 dBA, and tones at 89 dB SPL. The "noise" was either the pink noise or the hearing threshold, whichever was greater. The hearing loss was thresholds of 20, 30, 35, 40, 55, 90, and 90 dB SPL at 500, 1000, 2,000, 3,000, 4,000, 6,000, and 8,000 Hz, respectively. SNRs lower than -14 dB do not contribute to the SII.

1/3-Octave Band Number	1/3- Octave Band Center Frequency (Hz)	SNR for 0 dB HL thresholds	SNR for hearing loss	Band Importance
1	160	-0.2	-0.2	0.0083
2	200	2.8	2.8	0.0095
3	250	4.1	4.1	0.0150
4	315	4.3	4.3	0.0289
5	400	5.9	5.9	0.0440
6	500	6.6	6.6	0.0578
7	630	5.4	5.4	0.0653
8	800	-38.1	-38.1	0.0711
9	1000	-40.4	-40.4	0.0818
10	1250	-0.7	-0.7	0.0844
11	1600	-2.5	-2.5	0.0882
12	2000	-4.3	-4.3	0.0898
13	2500	-6.9	-6.9	0.0868
14	3150	-8.1	-8.1	0.0844
15	4000	-9.3	-24.2	0.0771
16	5000	-12.3	-46.5	0.0527
17	6300	-14.1	-64.1	0.0364
18	8000	-14.5	-64.5	0.0185

Appendix A-4

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

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Evaluation of communication during active sonar transmissions with a speech-recognition model

12. PERSONAL AUTHOR(S)
Lynne Marshall, Thomas E. Hanna, and Chaslav V. Pavlovic

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16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Speech-recognition; speech communication; intense tones; acoustic habitibility standards

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Predictions using the Speech Intelligibility Index (SII) are reported for speech recognition in tonal and broadband noise. Three levels of background pink noise (60, 65, and 70 dBA) were used for the SII. Tones in the frequency range around 1000 Hz at 77, 83, and 89 dB SPL were added to the background pink noise. The speech spectra were for four different vocal efforts (normal, raised, loud, and shouted). The simulated listeners for most of the predictions were assumed to have normal hearing. A hearing loss was also included for a subset of predictions. If "barely adequate" speech recognition is used as a criterion, the effects of the background noise can be overcome by increasing the vocal effort of the speaker, often to a shout.

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